

Supernovae and extragalactic astronomy with laser guide star adaptive optics

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ABSTRACT

Using the latest generation of adaptive optics imaging systems together with laser guide stars on 8m-class telescopes, we are finally revealing the previously-hidden population of supernovae in starburst galaxies. Finding these supernovae and measuring the amount of absorption due to dust is crucial to being able to accurately trace the star formation history of our Universe. Our images are amongst the sharpest ever obtained from the ground, and reveal much about how and why these galaxies are forming massive stars (that become supernovae) at such a prodigious rate.

Keywords: Supernovae, Luminous Infra-Red Galaxies, Laser guide star adaptive optics, NaCo, ALTAIR, GeMS

1. INTRODUCTION

Up to half of all the supernovae that should result when stars more massive than ~ 8 times the mass of our Sun reach the end of their lives and explode go unseen. This is starkly demonstrated in Fig. 1 which compares the discovery rate of core-collapse supernovae (CCSN) out to a redshift of ~ 1 , with the expectation from the increasingly well-defined measures of the star formation rate (SFR) in galaxies.¹ This deficit of supernovae is not for the lack of trying; many amateur and robotic supernova surveys monitor the sky every night and, even allowing for their incompleteness, there is a shortfall of a factor of 2 beyond our local Universe.

Our collaboration has pioneered the use of Laser Guide Star Adaptive Optics (LGSAO) facilities on the European Southern Observatory's Very Large Telescope (VLT) and on the Gemini North 8 metre telescope to begin revealing the mostly undiscovered population of CCSN within Luminous Infra-Red Galaxies (LIRGs). Being able to detect supernovae at infrared wavelengths in the dusty environments of LIRGs is critical in enabling us to determine the fraction of supernovae that will be missed by optical all-sky supernova searches such as those with the SkyMapper, KMTNet, and Large Synoptic Survey Telescopes (LSST), as well as satellite missions including Gaia, Euclid, and the James Webb Space Telescope (JWST). Here we describe the objectives, the practicalities, and the future prospects for the use of LGSAO in finding supernovae in LIRGs, while also revealing much about the nature of the LIRGs themselves.

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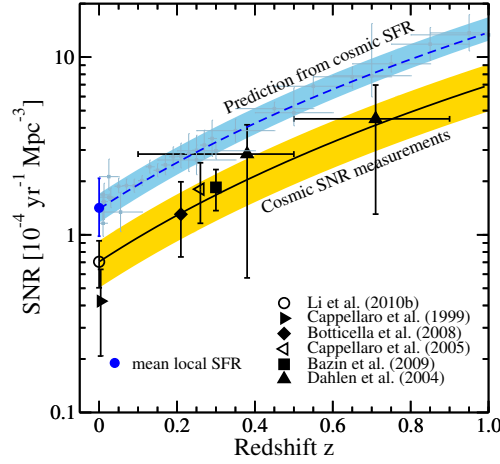


Figure 1. A demonstration of the “supernova rate problem”.¹ The CCSN rate predicted from the cosmic SFR history² is shown by the light grey points and blue band, while individual determinations of the CCSN rate at various redshifts are shown as black symbols and the yellow band. The predicted and measured cosmic CCSN rates are consistently discrepant by a factor of ~ 2 beyond $z \sim 0.2$.

2. BACKGROUND

2.1 The importance of supernovae

Core-collapse supernovae are one of the most important phenomena in all of astrophysics. If massive stars did not explode having exhausted their readily-available supplies of fuel for nuclear fusion, then none of the newly-synthesised heavier elements locked inside their cores would become available to the cosmos for subsequent generations of star (and planet) formation. CCSN are among the most energetic events in the Universe, releasing $> 10^{51}$ ergs in just a few seconds, generating shock waves which travel at tens of thousands of kilometers per second. They give rise to exotic remnants like black holes and neutron stars, trigger the collapse of gas clouds to form new stars, and appear to be the underlying source of gamma ray bursts and cosmic rays. It is crucial therefore that we have a complete census of where and how often they occur in the Universe.

Since the most massive stars which give rise to CCSN are also the shortest-lived, the CCSN rate is one of the most direct measures we have of the star formation rate. Since most of the SFR diagnostics used (e.g. $H\alpha$ and UV fluxes) and CCSN events both directly trace massive stars, this apparent supernova deficit in Fig. 1 is not caused by uncertainty about the form or universality of the Initial Mass Function (i.e. the relative numbers of high- and low-mass stars formed in any burst of star formation). Rather, the missed supernovae are either intrinsically much dimmer than the norm, and/or hidden from our view by significant dust extinction.

2.2 The importance of Luminous Infra-Red Galaxies

The class of so-called Luminous Infra-Red Galaxies (LIRGs) whose output in the infrared spectrum between 1 and $1000 \mu\text{m}$ exceeds 10^{11} times that of the Sun are thought to be some of most concentrated sites of both dust and star formation anywhere. The absorption of ultraviolet photons from the hot young stars by the dust, and its re-radiation at longer wavelengths, gives rise to their copious infrared luminosity. Together with their rarer but even brighter (by a factor of 10 or more) cousins, the Ultra-Luminous Infra-Red Galaxies (ULIRGs), LIRGs come to dominate the total SFR over that from normal spiral galaxies by a redshift of ~ 1 , when the Universe was less than half its present age.³

On the basis of their infrared luminosity and inferred SFR, LIRGs are expected to host in their nuclear regions about one CCSN per year on average. Thus LIRGs ought to be ideal “hunting grounds” ripe for CCSN discovery. Until quite recently only a few CCSN in LIRGs had been found.⁴ The reasons for this are twofold:

1. LIRGs are typically clumpy, complex structures by contrast with the much smoother elliptical and spiral galaxies. Combined with the fact that few LIRGs are closer than 50 million parsecs away, this makes spotting a transient point source against such a background particularly challenging.
2. The same dust which so efficiently absorbs light from the young stars may well completely obscure the supernova’s light, even when it briefly outshines all the other stars in the LIRG combined at optical wavelengths.

3. HUNTING FOR SUPERNOVAE IN LIRGS

3.1 The need for LGSAO

The first of these factors makes spatial resolution a high priority. Even in the best ground-based optical seeing $\sim 0''.5$, a CCSN within a few hundred parsecs of one of the bright nuclei of Arp 299 would not be resolvable. Fortunately Adaptive Optics (AO) facilities such as NaCo* on the VLT and ALTAIR† on the Gemini North telescope routinely deliver image quality as good as $\sim 0''.1$, albeit only within a small ($< 30''$) field of view, and only at near-infrared (1–2.5 μm) wavelengths.

The second factor motivates observing at near-infrared (NIR) wavelengths rather than optical, as the extinction (usually expressed on the logarithmic magnitude scale) due to dust is reduced by a factor of 10. Fortunately this is also the regime in which adaptive optics currently performs best.

The power of NIR AO searches for CCSN was first demonstrated by us with the discovery of SN 2004ip just 500 pc from the nucleus of the LIRG IRAS 18293-3413.⁵ The inferred extinction towards this event was at least 5 mag in V , and perhaps as high as 40 mag, meaning it would have gone unseen by any optical search. However very few LIRGs have a nucleus which is compact enough and bright enough at optical wavelengths to serve as the reference for on-axis AO correction, and not many meet the alternative requirement for an off-axis guide star. For example the ALTAIR facility on Gemini North requires that a $V < 11$ guide star be located within $25''$ of the target for full AO correction, or $V < 15$ for partial correction. Many of the most luminous LIRGs, which potentially offer the highest CCSN rates, simply have no suitable natural guide stars available. Fortunately the advent of LGSAO facilities on 8m class telescopes a decade ago relaxed this requirement somewhat, opening up many more LIRGs for CCSN searches. Nevertheless ALTAIR in LGSAO mode still requires a $R < 18$ tip/tilt star within $25''$ of the target for a low Strehl (up to 10% in K) correction.

3.2 Observing strategy

As mentioned previously, spotting a new point source like a CCSN against a complex background such as a LIRG is quite challenging. The standard approach to CCSN discovery is to subtract off a prior “reference” image of the LIRG host from the latest image (preferably with both images obtained by the same facility). Before subtraction the latest image must be rotated, shifted, and possibly scaled to match the earlier image using isolated field stars or other compact sources as a reference. The image with the better image quality as defined by the point spread function (PSF) width must be smoothed with a convolution kernel to match the image quality achieved in the other image, and the sky backgrounds and flux scales also adjusted to match. We use a slightly modified version of the Optimal Image Subtraction method⁶ as implemented in ISIS 2.2‡.

Any new point source residual in the pair-subtracted image is merely a CCSN candidate as other possibilities include:

- a passing minor planet. At AO resolutions the proper motion of a minor planet is usually detectable between, or even within successive exposures.

*<http://www.eso.org/sci/facilities/paranal/instruments/naco.html>

†<http://www.gemini.edu/sciops/instruments/altair>

‡<http://www2.iap.fr/users/alard/package.html>

- variable foreground stars, or variability of an Active Galactic Nucleus (AGN). The former are unlikely due to the typically small field of view, and either would show light curves compiled from follow-up observations that are inconsistent with that expected for a CCSN. Furthermore LIRGs can be selected on the basis of their *IRAS* colors to be dominated by star formation, rather than by an AGN.
- a thermonuclear (Type Ia) supernova. These events are thought to primarily trace lower mass star formation, with a much longer time delay ($\sim 10^9$ years). We expect perhaps 5% of all supernovae detected in LIRGs to be Type Ia and not a CCSN,⁵ and a radio detection would rule out a Type Ia event.⁷

By convention the International Astronomical Union’s Central Bureau for Astronomical Telegrams (CBAT) requires that before conferring an official designation, any CCSN candidate must be independently confirmed both by imaging on a different night and/or at a different facility, as well as by optical spectroscopy that allows assignment of a sub-type (e.g. Type Ia, Ib, Ic, IIP, IIL, IIB, IIn, etc.). Both of these requirements are problematic in our case, since LGSAO facilities are few in number and hard to win time on, while some of the CCSN candidates are so heavily extinguished by dust that obtaining an optical spectrum is impossible. Instead we make use of the fact that infrared emission from a CCSN tends to follow distinctive patterns.⁸ Furthermore, by monitoring how the flux of the CCSN evolves over many months in the 3 NIR bands *J* (centred on $1.25\ \mu\text{m}$), *H* ($1.65\ \mu\text{m}$), and *K* ($2.20\ \mu\text{m}$) and fitting these to templates of CCSN suffering almost no extinction, it is possible to derive the line-of-sight extinction due to dust, which is one of the key goals of our program. By measuring the extinction distribution in CCSN which are detected at NIR wavelengths, we can more realistically model the fraction of all CCSN which will be missed at optical wavelengths.

The last key to a successful CCSN survey is the cadence of observation, i.e. for a given amount of total observing time, what is the optimal interval between repeat observations of a LIRG? Observing each LIRG at monthly intervals say would almost guarantee that no CCSN bright enough at peak to be detected would be missed, but would rapidly exhaust all the available observing time. On the other hand, observing each LIRG only once per year would allow ample time for a CCSN event to peak and then fade from view in between observing epochs. Our simulations^{8,9} indicate that observations spaced 3–4 months apart yield the most efficient use of observing time, while minimising the risk of missing a CCSN event. Such a cadence favors observations in a queue mode, as the cost of so many visits (approximately monthly to monitor a sufficiently large number of LIRGs) to an LGSAO facility would be prohibitive.

3.3 Supernova discoveries

Over the course of 8 semesters between 2008 and 2012 we were allocated just over 50 hours with the ALTAIR LGSAO facility and Near InfraRed Imager (NIRI) on the Gemini North 8 m telescope on Mauna Kea to monitor 8 LIRGs for new CCSN. Each LIRG was imaged on average 7 times, at intervals of between 1 and 12 months but on average every 4.5 months. Each epoch of observation consisted of 9×30 sec dithered exposures on-source, followed by an equivalent set of exposures on adjacent blank sky as the LIRGs filled most of the NIRI field of view. The total elapsed time for each epoch including overheads was typically less than half an hour.

At the conclusion of our survey we discovered 4 new CCSN, and confirmed 2 more (Table 1) which had been detected independently. Just as importantly, we succeeded in obtaining *J*, *H*, and *K* light curves and/or radio follow-up^{10,11} for nearly all of them, to ascertain their line-of-sight extinctions, and confirm their core-collapse nature, respectively. The range in extinction probed ranges from effectively none, up to the equivalent of almost 20 magnitudes in the *V* band (i.e. only 1 in 40 million optical photons would make it through the dust). Figure 2 illustrates how one discovery can flow from the next, in that follow-up imaging of our discovery SN 2010cu in IC 883 yielded the discovery of SN 2011hi, the second CCSN in IC 883 within a year.

Our intensive monitoring of the LIRG Arp 299 has enabled us to build upon earlier efforts¹⁵ to derive the fraction of CCSN missed by optical surveys as a function of redshift¹⁶ (Fig. 3), which as mentioned in Section 1 has implications for current and future CCSN surveys, and even for the diffuse supernova neutrino background.¹⁷ Our corrections for the missing fractions of CCSN have been employed^{18,19} to show that most, if not all of the missing supernovae might be accounted for by dust extinction alone. But at low redshift statistical errors still dominate, so we need to increase the number of known CCSN in LIRGs before we can begin to discriminate between dusty and intrinsically dim CCSN.

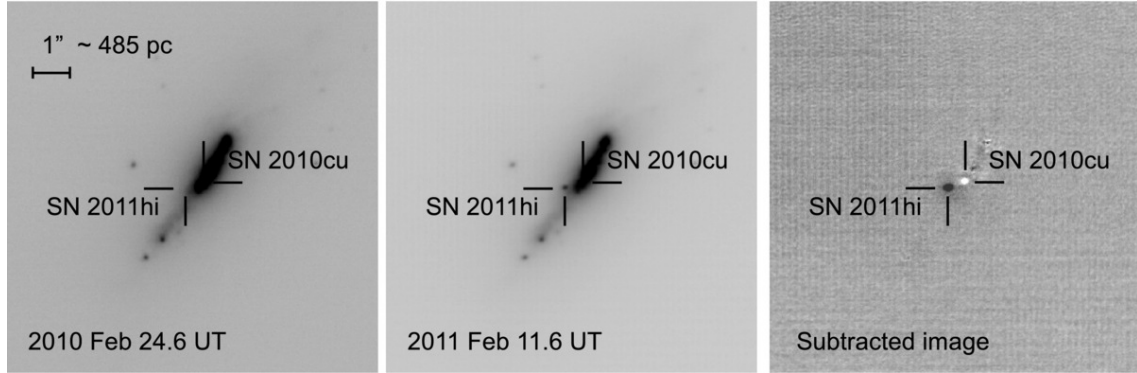


Figure 2. $10'' \times 10''$ subsections of *K*-band Gemini ALTAIR/NIRI LGSAO discovery images of SN 2010cu (left panel) and SN 2011hi (middle panel) and the subtraction between these two (right panel).¹⁴ The smooth subtraction of the host galaxy IC 883 clearly demonstrates the good alignment and PSF match between the images and the two SNe can be clearly detected as individual point sources thanks to the high-angular resolution provided by LGSAO. North is up and east is to the left.

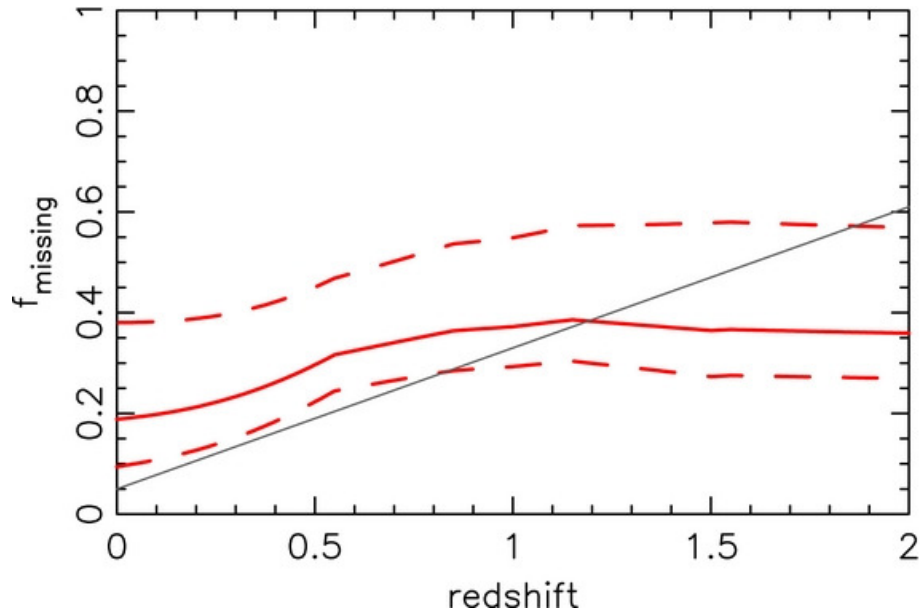


Figure 3. The fraction of CCSN missed by rest-frame optical searches as a function of redshift.¹⁶ Red lines show our best estimate together with the uncertainties indicated by the dashed lines. The solid grey line is the previous best estimate for the missing fraction.¹⁵

Table 1. Summary of supernovae discovered, or confirmed (SN 2010O, SN 2010P) by our Gemini North/ALTAIR laser guide star program, including line-of-sight extinction and projected distance from the LIRG nucleus.

Supernova	LIRG Host	Extinction A_V (mag)	Projected distance (pc)	Reference
SN 2004iq	IRAS 17138-1017	0–4	700	12
SN 2008cs	IRAS 17138-1017	17–19	1500	12
SN 2010O	IC 694 (Arp 299)	2	1100	13
SN 2010P	NGC 3690 (Arp 299)	7	1200	13
SN 2010cu	IC 883	0–1	200	14
SN 2011hi	IC 883	5–7	360	14

4. THE NATURE OF LIRGS

In addition to the CCSN discoveries we have made, one of the significant legacies that our work has delivered are some of the sharpest, deepest images of LIRGs ever obtained from the ground. While the triggering mechanism for prodigious star formation in LIRGs is believed to be mergers and interactions between two or more galaxies concentrating significant quantities of gas into their nuclei, very few of the LIRGs in our CCSN sample have been studied in any great detail individually. We have been using the best images from our Gemini/ALTAIR sample, as well as from an earlier VLT/NaCo survey, to glean new insights into the nature of the LIRGs themselves.

4.1 A triple merger

The LIRG IRAS 191152124 has been dubbed the “Bird” on account of its shape, which in NaCo K -band images resolves into two wings, a head, body, heart, and extended tail²⁰ (Fig. 4). By combining this image with data from the *Hubble Space Telescope* (HST) and *Spitzer* satellite, as well as optical longslit spectroscopy with the Southern African Large Telescope, we reach the surprising conclusion that the Bird contains not two, but three galaxies undergoing mutual interaction. The head, heart, and body are each separate galaxies of between 1 and 7×10^{10} solar masses, with the wings marking tidal tails. Strangely, despite being the least massive of the three galaxies, it is the head which is currently dominating star formation in the Bird.

4.2 Leading spiral arms

The LIRG IRAS 18293-3413 not only hosted our first AO CCSN discovery SN 2004ip,⁵ but also turns out to have unusual dynamics. HST optical images in Figure 5 show significantly more dust in silhouette towards the southwest, consistent with this edge of the galaxy disk being closer to us than the northeast edge. NIR longslit spectroscopy with the IRIS2 instrument on the Anglo-Australian Telescope indicates that the northwest side of the disk, facing the companion galaxy, is approaching us. Putting these two facts together we are led to conclude²¹ that the galaxy is turning clockwise in the image, i.e., in the same direction that the spiral arms clearly visible in the inset to Fig. 5 open out. Thus IRAS 18293-3413 is one of just a handful of known or suspected “leading arm” spirals. Such leading arms are predicted in simulations of retrograde encounters of a small companion galaxy²² as seen in IRAS 18283-3413.

4.3 Super star clusters

AO images of LIRGs show them to be extremely rich in what are referred to as “super star clusters” (SSCs; Fig. 6) having masses between 10^5 and 10^7 solar masses, ages of 10–100 million years, and sizes of just 3–5 parsecs. Analysis of the K -band luminosity functions of the SSC populations in our LIRGs²³ shows a power law with values of the index α ranging between 1.5 and 2.4 with an average value of 1.9, which is less steep than the average of 2.2 in normal spiral galaxies. Furthermore we have been able to demonstrate²⁴ that the luminosity of the brightest SSC in a LIRG scales with the galaxy’s total star formation rate, but with a steeper slope than a single optical to NIR conversion would imply.

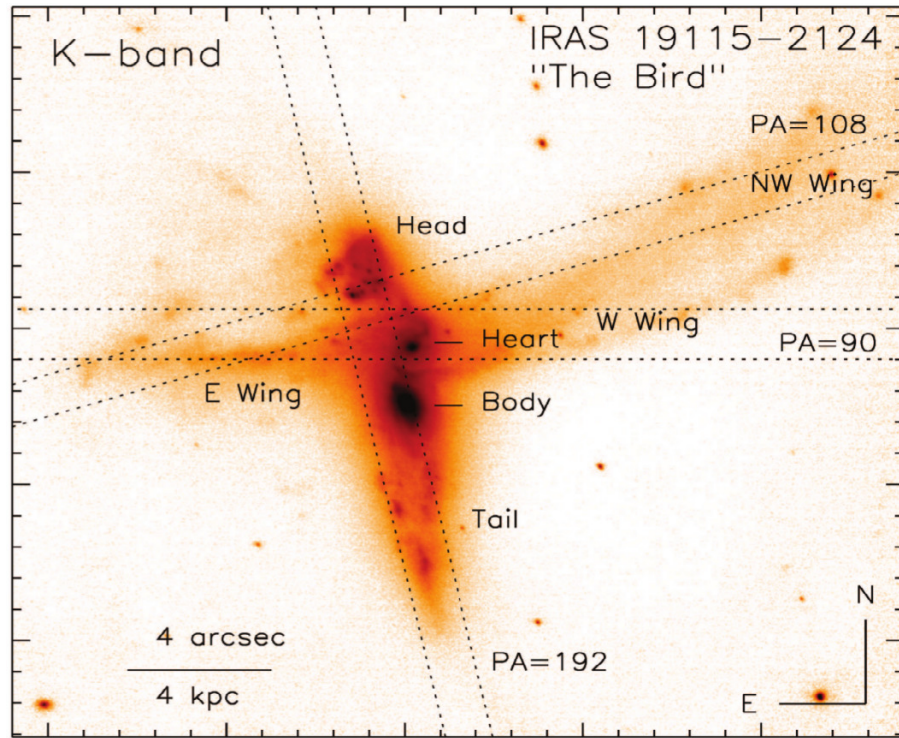


Figure 4. VLT/NaCo natural guide star AO image of the “Bird”, with the primary components indicated.

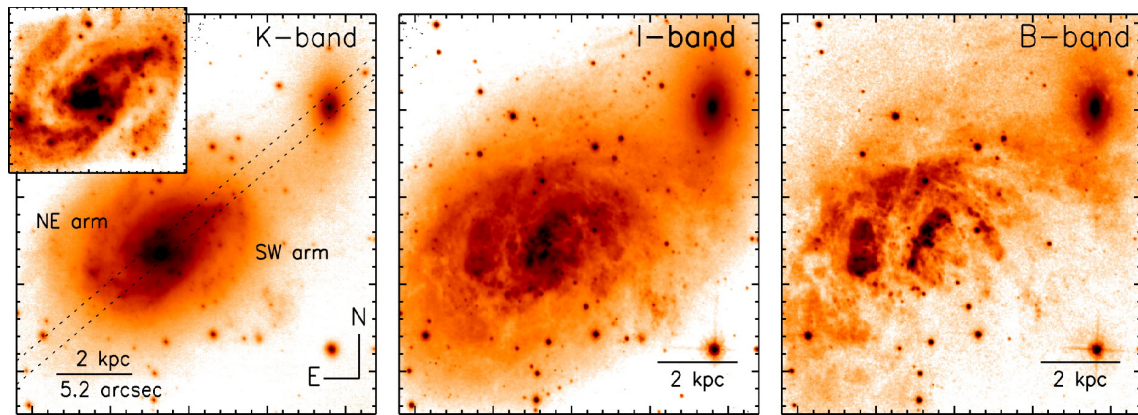


Figure 5. VLT/NaCo natural guide star AO image of the LIRG IRAS 18293-3413 (*left*), with the inset showing an unsharp masked image to highlight the arms in better contrast. The HST *I*-band (*middle*) and *B*-band (*right*) images are also shown.

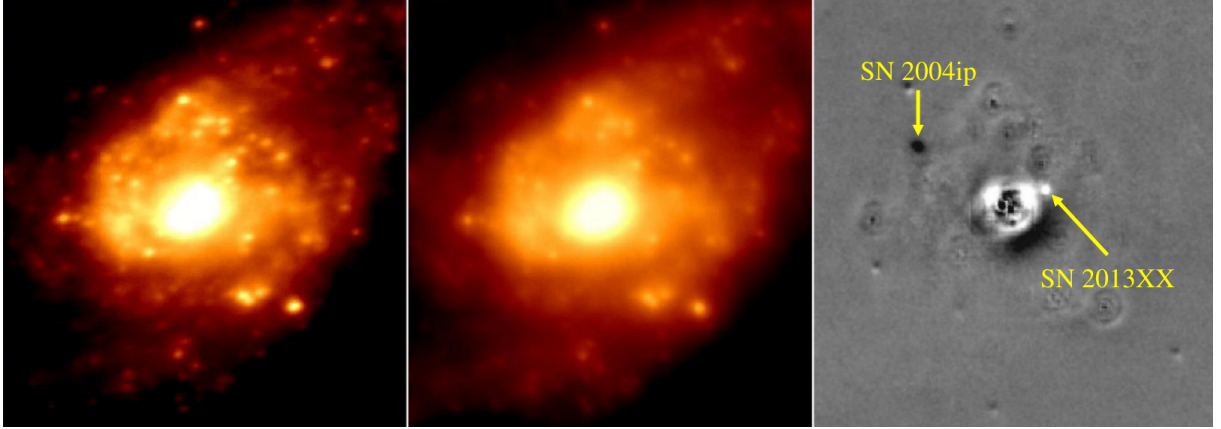


Figure 6. (*left*) K_s -band GeMS/GSAOI image of the LIRG IRAS 18293-3413 from 21 April 2013; (*middle*) a VLT NaCo image of the same LIRG from 2004; (*right*) an optimal image subtraction of the NaCo image from the GeMS image. The negative residual to the northeast is SN 2004ip discovered by us in our earlier NaCo program⁵ but which has long since faded from view; the positive residual $\sim 0''.5$ (~ 200 parsecs projected distance) to the northwest is a new supernova revealed in the GeMS image marked here as “SN2013XX”. Notice also the increase in the number of SSCs (Sec. 4.3) apparent in the new GeMS/GSAOI image due to the improvement in image quality.

5. THE FUTURE

To provide more meaningful constraints on the missing CCSN fraction we need to discover many more CCSN and have expanded our efforts to the Southern hemisphere making use of the superior new Gemini Multi-conjugate AO System (GeMS) feeding the Gemini South AO Imager (GSAOI) with its $85'' \times 85''$ field of view. We anticipate that the ability of GeMS to deliver a uniform PSF across the full GSAOI field will make for much improved image subtraction and photometric calibration compared with the “classical” LGSAO systems used to date, and potentially allow us to probe for CCSN even closer to the bright LIRG nuclei.

As an illustration of this potential, Fig. 6 shows our first epoch image with GeMS/GSAOI of the LIRG IRAS 18293-3413, compared with our previous best image from NaCo. In addition to highlighting the advance in AO performance in the past decade, these data nicely illustrate both our very first discovery of a CCSN with AO, SN 2004ip,⁵ as well as what we believe to be our first CCSN discovery with GeMS/GSAOI, marked here with the unofficial designation “SN 2013XX”. Thus we are confident that the next generation of LGSAO will leave little room for core-collapse supernovae to remain hidden within Luminous Infrared Galaxies.

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